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REPORT OF INVESTIGATIONS/1995

Numerical Modeling Analysis of Stress Transfer Modification Concepts for Deep Longwall Mines

UNITED STATES DEPARTMENT OF THE INTERIOR

UNITED STATES BUREAU OF MINES

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By Thomas L. Vandergrift and Charles V. Jude

UNITED STATES DEPARTMENT OF THE INTERIOR
Bruce Babbitt, Secretary

BUREAU OF MINES
Rhea Lydia Graham, Director

This report has been technically reviewed, but it has not been copy edited because of the closure of the agency.

CONTENTS

ILLUSTRATIONS

TABLES

UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

Metric Units

MPa	megapascal
m	meter
mt	metric ton

U. S. Customary Units

ft	foot
psi	pound per square inch
st	short ton
yd	yard
yr	year

NUMERICAL MODELING ANALYSIS OF STRESS TRANSFER MODIFICATION CONCEPTS FOR DEEP LONGWALL COAL MINING

By Thomas L. Vandergrift[1] and Charles V. Jude[1]

ABSTRACT

This U. S. Bureau of Mines (USBM) report evaluates three stress-transfer-modification concepts for their potential in reducing longwall gate road stresses and closures. In each of the three concepts — packwalling, gob infilling, and entry filling — support structures are constructed on the headgate side of the panel parallel with or inby the face line. When the headgate becomes the tailgate of the adjacent panel, these structures are in place to accept stresses transferred from the mined-out panel.

Using the USBM nonlinear boundary-element program MULSIM/NL, baseline models of typical longwall stress transfer behavior were developed for both intermediate depth and deep mining conditions. These models were verified by comparing model results with field measurements and observations. The stress-transfer-modification concepts were then incorporated into the deep baseline model to quantify the effects of each concept on tailgate closure.

Modeling results indicated that entry filling is the most effective concept in reducing tailgate escapeway closure. Using only 18 m^3 of a weak fill per meter of face advance (7.3 yd^3 per ft of face advance), tailgate escapeway closure was reduced by 33%. By improving the quality of the fill, similar results were achieved using 50% less volume.

INTRODUCTION

Many ground control problems encountered during longwall coal mining are caused by high abutment stresses in the gate road systems. These ground control problems range from relatively minor pillar spalling to violent failures such as floor heaves and coal bumps. Stability problems are especially severe in the tailgate, where they compromise the safety of mine personnel and threaten the integrity of the tailgate escapeway. The frequency and severity of stress-related ground failures will increase as deeper coal reserves are extracted and higher tectonic stresses are encountered. Over 50% of U. S. coal resources lie below 300 m (1,000 ft) of cover, and almost

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17% lie below 600 m (2,000 ft)(*1*).[2] Without effective gate road stress control methods for deep mining, major portions of deep coal resources will remain too hazardous and too costly to recover.

Current longwall mining practices implicitly assume that major portions of the load supported by the panel will be transferred to abutment zones in the gate road systems as the panel is mined. Under this assumption, gate road stress management has focused on pillar and artificial support design. This approach, although generally adequate for shallow mining (less than 600 m [2,000 ft]), is a passive response to conditions imposed by natural stress transfer processes. The U. S. Bureau of Mines (USBM) is studying more active approaches to stress control. The goal is to develop methods of influencing natural stress transfer processes so that stresses normally concentrated in active gate roads can be redirected to gob areas.

Longwall gob, which includes the caved area behind the face supports and other caved areas such as abandoned entries and crosscuts inby the face, makes up a major portion of the mine structure. It is essentially destressed, consisting of unconsolidated rubble with poor load-carrying capacity. If gob areas can be made to accept more overburden load, abutment stresses in the active gate roads and panel corners will be reduced.

In support of this goal, three stress-transfer-modification concepts have been proposed and analyzed:

(1) Packwalling behind the shields on the headgate end of the face.
(2) Gob infilling adjacent to the headgate entries.
(3) Entry and crosscut filling in the headgate inby the face.

In each of these concepts, structures with load-carrying capabilities superior to natural gob are created on the headgate side of the active panel. When the headgate becomes the tailgate of the adjacent panel, these structures are in place and can accept redistributed panel loads that would normally be carried by coal structures in the tailentry system.

The packwalling concept (figure 1*A*) involves the construction of monolithic packwalls inby the face adjacent to the headgate chain pillars. The packwalls would influence the caving behavior over the gob. The break line would be shifted farther into the gob area, and the packwalls would support a portion of the load transferred from the panel. This concept requires that the roof in the gob area behind the shields be temporarily supported until packwall construction is completed.

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[2]Italic numbers in parentheses refer to items in the list of references at the end of this report.

In the gob-infilling concept (figure 1*B*), the roof is allowed to cave as the face supports are advanced. The gob material adjacent to the headgate entries is then "rehabilitated" by filling the voids between the rubble with either a binder (cementatious) material or a filler (noncementatious) material. The infilled gob can then accept more of the load transferred from the panel.

Entry and crosscut filling (figure 1*C*) involves the construction of support structures in headgate areas that normally would be abandoned and allowed to cave after first panel mining. The structures would be emplaced parallel to or slightly outby the face line. These structures would serve two purposes: they would create additional support for loads transferred from the panel, and they would confine adjacent gate road pillars, thus increasing their load-bearing capacity. Roof conditions in the area of emplacement should be stable enough to allow the construction process to be completed without the necessity for additional roof support measures.

Initially, both backfilling and traditional wood cribbing were considered as construction methods for the packwalling and entry-filling concepts. However, wood cribs were eliminated from consideration because of their unacceptably low stiffness and high material cost. Barczak (2) reported crib stiffnesses of 4.5 to 59 MPa (650 to 8,500 psi) for wood cribs composed of 30% to 100% solids. The same report estimated the material cost for an installation of 1 cubic meter of cribbing at $59 to $200 ($45 to $150 per yd^3). Installation of wood cribbing is also very labor intensive.

Another advantage of backfilling over wood cribbing is that it offers the potential for environmental remediation. Stress-transfer-modification concepts utilizing backfill should be particularly applicable in areas where waste materials such as preparation and power plant refuse are readily available. These conditions exist primarily in the Eastern United States, and where about 25% of raw coal is rejected by the coal preparation plant as waste (*3*). Throughout the United States, coal combustion by-products are estimated at 82 million mt/yr (90 million st/yr) (*4*). Under the Clean Air Act of 1990, this number is expected to increase by 50% by the year 2000 (*5*).

Problems caused by mining under varying topography could also be solved by backfilling. In Eastern mines, cover depth variations of 240 m (800 ft) over a single panel are common (*3*). When mining under varying topography, the gate road layout for an individual panel could be designed for an intermediate overburden thickness occurring over the panel. As the panel is mined and deeper cover is encountered, fills containing coal combustion by-products and/or coal refuse could be placed to counter the effects of the increased overburden loads. This approach could result in increased coal recovery and decreased panel development costs while mitigating the environmental and economic consequences of surface waste disposal.

Theoretical and practical aspects of the packwalling, gob-filling, and entry- filling concepts were studied concurrently. Practical aspects were studied by identifying backfill preparation, transport, and placement issues pertinent to the task of achieving the concepts in the field. The results of the practical portion of the investigation are documented in a separate publication (*6*). This report summarizes the theoretical portion of the study. Numerical modeling analyses were performed to determine the potential of each stress-transfer-modification concept in reducing stress transfer to the gate roads. These analyses were performed using the USBM three-dimensional, nonlinear boundary-element program MULSIM/NL.

OVERVIEW OF MULSIM/NL

MULSIM/NL is a displacement-discontinuity boundary-element method (BEM) program for calculating mining-induced stresses and displacements in tabular deposits such as coal (*7, 8*). The distinguishing feature of MULSIM/NL is its nonlinear material models, which give the user the ability to model the nonlinear behavior of in-seam structures, such as yielding coal pillars. The program also includes a multiple mining step capability that allows stress and displacement changes to be calculated for different stages of mining. These stress and displacement changes can then be directly compared with field data, which usually reflect stress or displacement changes occurring after instrument installation.

Input to the program is relatively simple. The input file (figure 2) consists of three sections. The control section defines basic parameters, such as the model size, the properties of the surrounding rock (which is assumed to be linear-elastic), the properties of seam materials (which can be nonlinear), the in situ stress field, the depth of excavation, and the number and orientation of parallel seams (up to four). The second and third sections consist of fine and coarse meshes that define the mine layout and the distribution of materials within the seam. The coarse mesh surrounds the fine mesh and describes the generalized geometry and material distribution of the model using coarse "blocks." "Elements" in the fine mesh each cover 1/25th the area of the coarse mesh blocks and describe the geometry and seam property distribution of the region of interest in greater detail.

Both the coarse and fine mesh sections consist of alphanumeric characters that correspond to stress-strain relationships defined in the control section of the input file. Zeros in the coarse mesh indicate the section of model that is described in detail in the fine mesh. The six types of seam material models available in MULSIM/NL are shown in figure 3.

MULSIM/NL can be run in a PC environment, although models run on a workstation take significantly less time. The program is easily learned, simple to use, and is an effective tool for quantifying the effects of changing material properties and mining geometries.

DEVELOPMENT OF STRESS TRANSFER BASELINE MODELS

In order to perform a numerical analysis of the proposed stress-transfer-modification concepts in reducing stresses and improving stability in the gate roads, a basis for comparison, or baseline model, was needed. By comparing stress and closure magnitudes between the baseline model and models incorporating the stress transfer modification concepts, the effects of the modification concepts can be quantified.

Baseline models of typical longwall stress transfer behavior were developed in two phases. In the first phase, a baseline model of an intermediate depth (335 m [1,100 ft]) Western longwall was developed. Geotechnical and borehole pressure cell (BPC) data collected using the USBM Ground Control Management System (GCMS) were analyzed to develop appropriate material property input to this model. To test the ability of the intermediate depth baseline model to predict real-world stress transfer behavior, the material properties developed from the data analysis were incorporated into a model of an experimental gate road test section at the mine. Ground pressure data from the instrumented test section were then compared with modeling results.

Using the experience gained from the development of the intermediate depth model, the second phase of baseline model development was begun. In this phase, a deep baseline model was developed based on published results from studies in Eastern and Southeastern deep (~625 m [~2050 ft]) longwall mines. This deep baseline model was then used to quantify the effects of the various stress-transfer-modification concepts.

Intermediate Depth Model

The creation of a MULSIM/NL model involves three major steps: definition of overall model parameters, input of the mining geometry, and input of the seam material properties. The first two steps are relatively easy; known parameters are input, and blocks and elements are arranged in a grid corresponding to the mine layout. The key to creating a realistic model of typical longwall stress transfer behavior lies in the choice and proper distribution of seam material properties. Material properties for the intermediate depth baseline model were chosen after an analysis of extensive BPC data from a Western longwall mine under 335 m (1,100 ft) of cover. The mine produces coal from a 3-m (10-ft) thick coal seam in panels approximately 195 m (640 ft) wide by 3,050 m (10,000 ft) long using a three-entry gate road system. The gate road system is comprised of one small pillar (10 m wide by 24 m long [35 ft by 80 ft]) adjacent to the headgate and one large pillar (about 24 m [80 ft] square) adjacent to the tailgate. Figure 4 shows the general mine layout and the location of various USBM instrumentation sites.

The ground pressure data, monitored and collected using the GCMS developed by the USBM (*9-10*), covered pillar instrumentation sites 1 through 5 (figure 4). These five sites represented mining in three different panels over the course of 2-1/2 years. The BPC readings from instrumentation site 2 (figure 5) are representative of the typical ground pressure data observed in the five instrumentation sites. BPC pressure readings for site 2 during the mining of panels 1 and 2 are given in figures 6*A* and 6*B*, respectively.

To develop seam material properties from the BPC data, a rationale for converting BPC pressure changes to ground stress was needed. Several techniques for accomplishing this have been proposed (*11*); however, they require data beyond that available from the vertically oriented pressure cells in the five instrumentation sites. The pressure cells were not installed specifically for the modeling effort, nor to gather absolute stress data, but rather as part of a complementary USBM research effort to measure trends in the distribution of loads in the panel and gate road pillars. Therefore, a simplifying assumption based on a review of earlier studies (*11*) relating cell data to ground stress was made. The vertical stress within the coal structures was assumed to be 80% of the pressure change recorded by the pressure cells after installation plus the preexisting vertical stress of 8.3 MPa (1,210 psi).

Of the six stress-strain material models available in MULSIM/NL, two were used in the development of the intermediate depth baseline model: the strain-softening model for coal and the strain-hardening model for gob. Stress-strain curves for these material models are shown in figure 7. Each of the coal elements has an initial modulus of 3,450 MPa (500,000 psi). The BPC data analysis suggested that the coal exhibited three distinct types of mechanical behavior based on its degree of confinement. Elements for yield zones within 3 m (10 ft) of an opening yield at 31 MPa (4,500 psi) and have a residual strength of 16.6 MPa (2,400 psi). Confined coal in the panel and the core of the large pillars are modeled to have a peak strength of 48 MPa (7,000 psi), after which they slowly yield to a residual strength of 24 MPa (3,500 psi). The core of the small pillars is modeled to have a peak strength of 41 MPa (6,000 psi) and a residual strength of 27.5 MPa (4,000 psi).

Based on values given by Peng (*12*), Pappas (*13*), and on results from laboratory compression tests on aggregate performed by the author, the strain-hardening model for gob was given an initial modulus of 103 MPa (15,000 psi) and a final modulus of 345 MPa (50,000 psi).

Properties of the rock surrounding the seam were based on laboratory compression tests of core samples. Overall model parameters, defined in the control section of the input file, are summarized in table 1.

Figure 8 shows the in-seam vertical stress distribution of the intermediate depth baseline model. Outby the face in the headgate of the active panel, the stress distribution arises from the development of the gate road entries. Abutment stresses associated with panel mining are not evident until the face is about 30 m (100 ft) inby.

This front abutment is characterized by rapidly increasing stress levels near the face line in the panel, the small pillar, and the larger pillar. Further inby along the headgate entries, the ribs of the small pillars yield when the face is between 0 to 30 m (0 to 100 ft) outby. The cores of these pillars also yield when the face is about 30 to 60 m (100 to 200 ft) outby. The large pillars show increased loading on the gob side of the active panel, with some indication of rib yielding about 120 m (400 ft) inby the face.

In the tailgate, the small pillars and the ribs of the large pillars have completely yielded. The presence of the front abutment is evidenced in the core of the large pillars, which show increased stresses near the face. Inby the face, the large pillar cores are heavily loaded.

The stress distribution of the model generally agrees with in-mine observations of ground conditions and yield sequences. To further test the ability of the model to represent real-world stress transfer processes, material properties developed for the model were used to model an experimental gate road layout at the mine (see instrumentation site 6, figure 4). Figure 9 shows the geometry of the experimental gate road layout and the location of borehole pressure cell instrumentation. In addition to the empirical approach to material property development described above (figure 10, model "B"), a second, more intuitive approach to material property development was also taken (figure 10, model "A"). Two series of models were run, with 23 models in each series, to simulate various face positions inby and outby the instrumentation site for both first panel (Panel 4) and second panel (Panel 5) mining.

In general, the results from both modeling approaches showed good correlation with BPC stress patterns on first panel mining. The response of coal structures to first panel mining was, for the most part, elastic, with only minor sloughing of the gob side of the large pillar. On second panel mining, however, more yielding occurred, and stress changes in the BPC's were significantly higher than in the models (figure 11). Although the magnitudes of stress changes were underestimated by the models, the sequence of element yielding corresponded with coal yielding as indicated by the BPC data. Further details of the comparison between modeling and field instrumentation results can be found in a previous USBM report by Cox (*14*).

Deep Baseline Model

With the experience gained from the development of the intermediate depth baseline model and the comparison of modeling results with instrumentation data, a baseline model of deep longwall mining conditions was developed. The proposed stress-transfer-modification methods should be particularly applicable in deep mines where poor tailgate conditions are caused by the high abutment stresses associated with deep cover.

The mine layout and material properties for the deep baseline model were based on published reports from studies in deep mines in the Eastern and Southeastern United States (*3, 15-17*). These mines, located in southwestern Virginia and central Alabama, represent some of the deepest coal mining conditions in the United States. They have many similar characteristics, including seam properties and gate road layout (*16*).

The deep baseline model was more closely patterned after the southwestern Virginia example because of the availability of field data and observations from previous USBM research (*3, 17*). Basic model parameters are given in table 2. In the area modeled, coal was mined from a 1.7-m (5.5-ft) thick seam in panels approximately 185 m (600 ft) wide by 1,830 m (6,000 ft) long. For ventilation purposes and for entry stability, the mine employs a 72-m (240-ft) wide, four-entry gate road system with a yield-abutment-yield pillar configuration (figure 12). The 37- by 55-m (120- by 180-ft) abutment pillars, driven on 43-m (140-ft) centers, are designed to carry abutment loads resulting from adjacent gob formation, thereby reducing abutment loading on the tailgate corner of the active panel. They are flanked by 6- by 24-m (20- by 80-ft) yield pillars. The crosscuts between the yield pillars are angled at 60° on 30-m (100-ft) centers.

By varying the stress-strain characteristics of the seam elements, a MULSIM/NL model was created whose behavior closely matched stress transfer behavior observed in the field. Two seam material models were used — the strain- softening model for coal and the strain-hardening model for gob. The seam element properties developed for this model are shown in figure 13.

Confined coal in the panels and in the core of the abutment pillar were assigned an initial modulus of 2,410 MPa (350,000 psi), a yield strength of 72 MPa (10,500 psi), and a residual strength of 21 MPa (3,000 psi). The yield strength of confined coal structures, based on measurements taken by USBM researchers, is about seven times the unconfined compressive strength of the coal at the mine. This unusually high triaxial strength factor is apparently due to highly competent roof and floor members, especially the thick quartz arenite sandstone of the main roof (*3*). The yield pillars and yield zones within the first 3 m (10 ft) of the panel edges were represented by elements with an initial modulus of 2,410 MPa (350,000 psi), a yield strength of 36 MPa (5,250 psi), and a residual strength of 16 MPa (2,260 psi). The strain-hardening gob was given an initial modulus of 34 MPa and a final modulus of 345 MPa (5,000 and 50,000 psi, respectively).

Figure 14 shows the vertical stress distribution of the deep baseline model during first panel mining (part *A*, as the gate road serves as the headgate) and second panel mining (part *B*, as the gate road serves as the tailgate). During first panel mining, the yield pillars adjacent to the active panel yield about 60 m (200 ft) outby the face line. Their counterparts on the opposite side of the abutment pillars yield in line with the face. Only the periphery of the abutment pillars inby the face yield, with the cores of the abutment pillars showing increased loading due to the side abutment, especially on the side adjacent to the gob. Front abutment pressures are evident in the active panel beginning about 30 m (100 ft) outby the face.

During second panel mining, both rows of yield pillars, as well as the periphery of the abutment pillars, have completely yielded, both inby and outby the face. The abutment pillars are heavily loaded, and yield when the face is about 55 m (180 ft) inby. The yielding of the abutment pillars leads to increased closure in the tailgate escapeway adjacent to the panel. It is expected that the high closure indicated by the model would correspond with poor ground conditions in the escapeway.

A qualitative comparison between characteristics of the model and in-mine measurements and observations reported by Campoli (*17*) is given in table 3. A more quantitative comparison is given in figures 15 and 16. As was the case with the intermediate depth baseline model, there is good correlation between the sequence of element yielding in the model and coal structure yielding observed in the field.

NUMERICAL MODELING ANALYSIS OF STRESS-TRANSFER-MODIFICATION CONCEPTS

With an acceptable model of typical longwall stress transfer behavior under deep mining conditions in place, a numerical analysis of the three stress-transfer-modification concepts was performed. The major variables of the stress-transfer-modification concepts are the mechanical properties and geometric extent of the fill materials. Using MULSIM/NL, an analysis of these variables was performed over the range of values considered possible in field application.

Fill Property Development

In developing the baseline models, a rationale was needed for developing properties of the in-seam materials. Similarly, a rationale for developing fill material properties was needed for the analysis of the packwalling, gob-filling, and entry-filling concepts.

In practice, the choice of a particular fill material, as well as methods for its handling, transport, and placement, depends on a number of site-specific factors. These factors include the local availability of the material, its chemical and physical characteristics, and the strength and stiffness required to achieve improvements in gate road stability. The latter factors are heavily influenced by the depth and geological setting of the coal seam. Because the analysis of the three stress transfer modification concepts was general rather than site specific, the factors that influence fill material selection were undetermined, and a specific fill material could not be modeled.

Instead, a range of fill qualities were modeled based primarily on fill stiffness and its relationship to fill strength.

Ideally, the backfill material would have at least the stiffness of the coal that it is replacing. In the case of the deep baseline model, the coal stiffness is 2,400 MPa (350,000 psi). A review of laboratory test results on slurries containing fly ash (*18*) and coal prep plant refuse (*19*) revealed that, with proper gradation of aggregate and suitable cement content, stiffnesses of up to 6,900 MPa (1,000,000 psi) could reasonably be achieved. Based on this, six different fills were modeled, with stiffnesses starting at the upper bound of 6,900 MPa (1,000,000 psi), and decreasing by a factor of two in each subsequent fill, for a range of 216 to 6,900 MPa (31,250 to 1,000,000 psi). To input stress-strain relationships for each of the fills into MULSIM/NL, assumptions were required regarding the nature of the fill materials. Factors considered included yield strength, residual strength, and the relationships between (1) modulus and unconfined compressive strength, (2) unconfined compressive strength and yield strength, and (3) prefailure and postfailure modulus. The assumptions and their rationale are given below:

(1) Fills were divided into three categories — gob fill, confined monolithic fill, and unconfined monolithic fill (fill within 3 m (10 ft) of a free surface). Fills for the gob-infilling concept were assumed to behave similarly to cemented rockfill used in hard-rock mines, and were modeled using elastic-plastic material elements. Monolithic fills for the packwalling and entry-filling concepts were assumed to behave similarly to concrete. Because their postfailure behavior would be similar to a consolidated rubble pile, they were modeled using elements with both elastic-plastic and strain-softening characteristics.

(2) The relationship between modulus and unconfined compressive strength for the gob fill was based on empirical data on cemented rockfills. Using data from 33 mine fills, Swan (*20*) found the following relationship:

$$E = 23.02(\sigma_c)^{1.18}, \tag{1}$$

where E = deformation modulus,
σ_c = compressive strength.

The relationship between modulus and unconfined compressive strength for the monolithic fills was based on a rule-of-thumb for concrete that gives modulus as 1,000 times unconfined compressive strength (*21*).

(3) Yield strength for the gob fill was conservatively estimated to equal the unconfined compressive strength calculated from equation 1. Yield strength for the confined monolithic fill was calculated by taking its assigned

modulus, dividing by 1,000 to calculate unconfined compressive strength, and multiplying by 7, the triaxial strength factor of the deep baseline model. Similarly, a yield strength for the unconfined monolithic fill was taken as 3.5 times the unconfined compressive strength.

(4) Based on experience gained from the deep and intermediate depth baseline models, residual strength for the unconfined monolithic fill was capped at the cover stress of 15.5 MPa (2,260 psi). For the confined monolithic fill, a residual strength of 20.7 MPa (3,000 psi) was used.

(5) Postyield modulus of the gob fill was assumed to equal the final modulus of unfilled gob, 345 MPa (50,000 psi). For the monolithic fills with yield strengths below their ultimate residual strength, postyield modulus was estimated at 25% of the original modulus.

Stress-strain curves for all of the fills used in the numerical analysis are given in figure 17. Although the assumptions these curves are based on may not strictly hold true for any specific fill, the goal was to model the range of fill properties that could reasonably be expected in the field. Later, a specific fill could be field tested to determine its in situ behavior.

Variations in Fill Geometry

To establish the amount of fill material needed for effective gate road stress control, different fill geometries were modeled in each of the stress transfer modification concepts.

The gob-filling and packwalling concepts shared similar geometries, as shown in figure 18*A*. The minor difference is that packwalls were modeled adjacent to the gob side yield pillars, whereas the gob infilling models included a 3-m (10-ft) buffer zone of unfilled gob between the gob fill and the yield pillars. Models with strips of either gob fill or monolithic fill 3 m, 9 m, 15 m, 30 m, and 61 m wide (10 ft, 30 ft, 50 ft, 100 ft, and 200 ft wide, respectively) were run for each concept. In addition to the slight difference in geometry between the gob-filling and packwalling models, the gob-filling model took into account caving height, which was assumed to be three times the seam thickness. Therefore, for equal fill stress levels, the gob-infilling model would give fill closures three times that of the packwalling model.

Four fill geometries were modeled in the analysis of the entry-filling concept (figure 18*B*). Fills were modeled in the crosscuts between the yield pillars adjacent to panel 1, in the entry adjacent to the panel 1 side of the abutment pillars, in the crosscut between the abutment pillars, and in the entry on the panel 2 side of the abutment pillars. Fill volumes were cumulative for each successive modeling run.

Fill volumes for each of the modeling runs are expressed in table 4 in terms of volume per unit of face advance and volume per unit of panel coal mined. These values are based on the 1.7-m (5.5-ft) seam height and the 185-m (600-ft) panel width of the deep baseline model.

Modeling Results

With the combination of fill properties and geometries described, a suite of 84 MULSIM/NL models was run to determine the effects of the gob-infilling, packwalling, and entry-filling concepts on gate road stability.

To effectively model the effects of fill sequencing and placement, a modification to the MULSIM/NL code was requested through the program developer. Prior to the modification, insertion of fill material would reduce stress levels in adjacent yielded coal structures to below their yield point, causing them to "unyield." The new element-birth option (*22*) makes stress and displacement calculations path-dependent. Using the modification, the problem of unrealistic "unyielding" of coal structures has been overcome.

Of primary importance in longwall mining, both from a safety and regulatory standpoint, is the integrity of the tailgate escapeway. As a criterion for comparing modeling results, total closure in the tailgate escapeway area outby the face, as indicated on figure 19, was calculated for each model. These closures were then compared to closure in the same area of the deep baseline model, and reductions in tailgate escapeway closure were calculated on a percentage basis.

In analyzing the modeling results of the various stress-transfer-modification concepts, it became obvious that the yielding of the 37- by 55-m (120- by 180-ft) abutment pillar was the main control on tailgate escapeway closure. If stresses in the abutment pillar could be limited to prevent it from yielding, resulting closures in the tailgate escapeway were greatly reduced. As an example, the vertical stress and closure distributions for the tailgate of the deep baseline model with and without backfilling are shown in figures 20*A* and 20*B*. Without backfilling, the tailgate abutment pillars have yielded both inby the face and for about 55 m (180 ft) outby (figure 20*A*). Using an intermediate strength fill in the crosscuts and in the entries on either side of the abutment pillar, stress levels in the abutment pillars remain below their yield strength (figure 20*B*). Figure 20*C* shows the differences in closure between the baseline model and the model with backfilled entries. In the entry-fill model, tailgate escapeway closure is greatly reduced, in this case by 38%.

A summary of the effectiveness of the stress-transfer-modification concepts in reducing tailgate escapeway closure is given in figure 21. In most cases, the entry-filling concept produced greater reductions in escapeway closure per unit of fill volume than did the packwalling and gob-filling concepts. Even a very weak entry-fill

(1.5 MPa [220 psi] compressive strength, 216 MPa [31,250 psi] deformation modulus) produced significant reductions in tailgate escapeway closure (figure 21*A*). For this material, an entry-fill volume of 18 m^3 per meter of face advance prevented the abutment pillars from yielding and gave a 28% reduction in tailgate escapeway closure. In all cases, fill volumes beyond those required to prevent the abutment pillar from yielding produced only marginal improvements in tailgate escapeway closure.

SECONDARY ANALYSIS OF ENTRY-FILLING CONCEPT

In the numerical analysis, the entry-filling concept outperformed the other stress-transfer-modification concepts in reducing tailgate escapeway closure. In addition, it has obvious practical advantages over the packwalling and gob-filling concepts. Unlike the gob-filling concept, the volume to be filled would be well established, with boundaries defined by the ribs of the gate road pillars. Unlike the packwalling concept, additional roof support measures would not be needed since the roof in the area of emplacement should be stable. Because of these practical and theoretical advantages, a more detailed numerical analysis of the entry-filling concept was performed.

Of the six materials modeled in the original analysis, three were modeled in the detailed analysis. These were monolithic fills 1, 3, and 5, as indicated on figures 17*B* and 17*C*. The three fills represent a range of modulus values from 216 MPa to 3,450 MPa (31,250 psi to 500,000 psi).

In the original analysis of the entry-filling concept, fill was modeled to begin on the first panel side of the gate road system and to progress toward the second panel side. This was done to minimize abutment stresses in the fill near the tailgate escapeway. However, the modeling results indicate that this should not be a problem, as stresses in the fill never reached high levels. Therefore, for maximum effectiveness in reducing escapeway closure, fill was modeled in the detailed analysis to begin on the second panel side of the gate road and progress toward the first panel side. Eight different geometries of fill were modeled, as shown in figure 22. Of the eight geometries, five (figures 22*A* through 22*E*) allow for one open entry and three (figures 22*F* through 22*H*) allow for two open entries. The associated fill volumes, expressed both in terms of volume per unit of face advance and volume per unit of panel coal mined, are also given in table 5. By combining the three fill materials and the eight fill extents, a suite of 24 MULSIM/NL models of the entry-filling concept was created and run.

The results from the detailed analysis of the entry-filling concept are summarized on figure 23. Both the one open entry and the two open entry configurations were effective in preventing abutment pillar yielding and in producing reductions in tailgate escapeway closure. The choice of one configuration over the other would have to be evaluated on a site-by-site basis. As with the original analysis, even the weakest fill was effective. A weak fill (1.5 MPa [220 psi] compressive strength, 216 MPa [31,250 psi] deformation modulus) volume of 18 m^3/m of face advance (7.3 yd^3/ft of face advance) was sufficient to prevent abutment pillar yielding and to reduce tailgate escapeway closure by 33%. The model results indicate that with the intermediate strength fill (6 MPa [875 psi] compressive strength, 860 MPa [125,000 psi] deformation modulus), similar reductions in escapeway closure can be achieved using 50% less volume. With the intermediate strength fill, 12 m^3/m of face advance (4.9 yd^3/ft of face advance) gave an escapeway closure reduction of 36%. These results are encouraging; they suggest that significant improvements in tailgate stability can be achieved using limited amounts of relatively low-strength fill.

CONCLUSIONS

Effective gate road stress management will be essential if deep coal reserves are to be mined safely and efficiently using the longwall method. By modifying natural stress transfer processes, it may be possible to redirect abutment stresses to gob areas, thereby reducing stresses in the gate road systems.

Of the stress-transfer-modification concepts analyzed using the boundary-element code MULSIM/NL, the entry-filling concept was the most effective in reducing stress and closure levels in the vital tailgate escapeway. Just 18 m^3 of a weak fill per meter of face advance (7.3 yd^3 per ft of face advance) resulted in a reduction in tailgate escapeway closure of 33%. By improving the quality of the fill, similar results were achieved using 50% less fill volume. In addition to the theoretical advantages brought out by the numerical analysis, the entry-filling concept has obvious practical advantages over the gob-filling and packwalling concepts.

The entry filling-concept has the potential to enhance the stability of gate road entries while simultaneously helping to remediate surface waste disposal problems. Entry filling should be particularly applicable in the Eastern United States, where disposal of reject materials from coal preparation plants and electric power plants is a special concern. In hill-and-valley topographies common in the East, entry filling could be used to optimize panel layouts, thereby increasing coal recovery and reducing gate road development costs.

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Table 1.—Basic model parameters for intermediate depth baseline model

Parameters	*Input data*	
Block dimension, m × m (ft × ft)	15.2 × 15.2	(50 × 50)
Depth of seam, m (ft)	335	(1,100)
Element dimension, m × m (ft × ft)	3.0 × 3.0	(10 × 10)
Rock strata modulus, MPa (psi)	9,650	(1.4×10^6)
Seam thickness, m (ft)	3.0	(10)

Table 2.—Basic model parameters for deep baseline model

Parameters	*Input data*	
Block dimension, m × m (ft × ft)	15.2 × 15.2	(50 × 50)
Depth of seam, m (ft)	625	(2,050)
Element dimension, m × m (ft × ft)	3.0 × 3.0	(10 × 10)
Rock strata modulus, MPa (psi)	6,890	(1.0×10^6)
Seam thickness, m (ft)	1.7	(5.5)

Table 3.—Comparison of in-mine observations and deep baseline model results

	Field observation	Model result
First panel mining	Yielding of panel rib in the headgate about 12-18 m (40-60 ft) outby the face.	Similar yielding 37 m (120 ft) outby the face.
	Yield zone in panel rib in the headgate is between 1.5 and 3 m (5 to 10 ft).	Yield zone is 3 m (10 ft).
	Yield zone around perimeter of abutment pillars when the face is between 0 to 60 m (0 to 200 ft) outby.	Similar yielding when the face is 21 m (70 ft) outby.
	Yield pillars on far side of abutment pillars yield when the face is 60 to 90 m (200 to 300 ft) outby.	Similar yielding parallel to the face line.
	Edge of adjacent panel yields when face is 90 to 120 m (300-400 ft) outby face.	Similar stress buildup, although yielding not evident within 120 m (400 ft) inby.
Second panel mining	Abutment pillars not affected by second panel mining until face within 60 m (200 ft); then first panel side of abutment pillars fail.	Similar pattern, although failure of first panel side of abutment pillars noted when face within 115 m (380 ft).
	Abutment pillar totally failed when face within 30 m (100 ft).	Similar yielding when face 55 m (180 ft) inby.
	Maximum front abutment stress change of 79 MPa (11,500 psi).	Maximum stress change set at 57 MPa (8,240 psi).

Table 4.—Fill volumes for stress transfer modification models

Model type	Fill extent[1]	Fill Volume			
		m^3/m face advance	yd^3/ft face advance	m^3/mt coal	yd^3/st coal
Gob infilling/ packwalling	3 m (10 ft) strip	5.1	2.0	1.3×10^{-2}	1.5×10^{-2}
	9 m (30 ft) strip	15.3	6.1	3.8×10^{-2}	4.5×10^{-2}
	15 m (50 ft) strip	25.5	10.2	6.3×10^{-2}	7.5×10^{-2}
	30 m (100 ft) strip	50.9	20.4	1.3×10^{-1}	1.5×10^{-1}
	61 m (200 ft) strip	101.9	40.7	2.5×10^{-1}	3.0×10^{-1}
Entry filling	Yield pillar crosscuts	2.0	0.8	5.0×10^{-3}	6.0×10^{-3}
	Above plus entry 1	12.2	4.9	3.0×10^{-2}	3.6×10^{-2}
	Above plus abutment pillar crosscuts.	18.3	7.3	4.5×10^{-2}	5.4×10^{-2}
	Above plus entry 2	28.5	11.4	7.1×10^{-2}	8.4×10^{-2}

[1]Shown in figure 18.

Table 5.—Fill volumes for the detailed analysis of the entry-filling concept.

Figure showing fill geometry	Fill volume			
	m^3/m face advance	yd^3/ft face advance	m^3/mt coal mined	yd^3/st coal mined
22*A*	2.0	0.8	5.0×10^{-3}	6.0×10^{-3}
22*B*	12.2	4.9	3.0×10^{-2}	3.6×10^{-2}
22*C*	18.3	17.3	4.5×10^{-2}	5.4×10^{-2}
22*D*	28.5	11.4	7.1×10^{-1}	8.4×10^{-1}
22*E*	22.4	9.0	5.6×10^{-1}	6.7×10^{-1}
22*F*	6.1	2.4	1.5×10^{-3}	1.8×10^{-3}
22*G*	16.3	6.5	4.1×10^{-2}	6.0×10^{-2}
22*H*	10.2	4.1	2.6×10^{-2}	3.1×10^{-2}

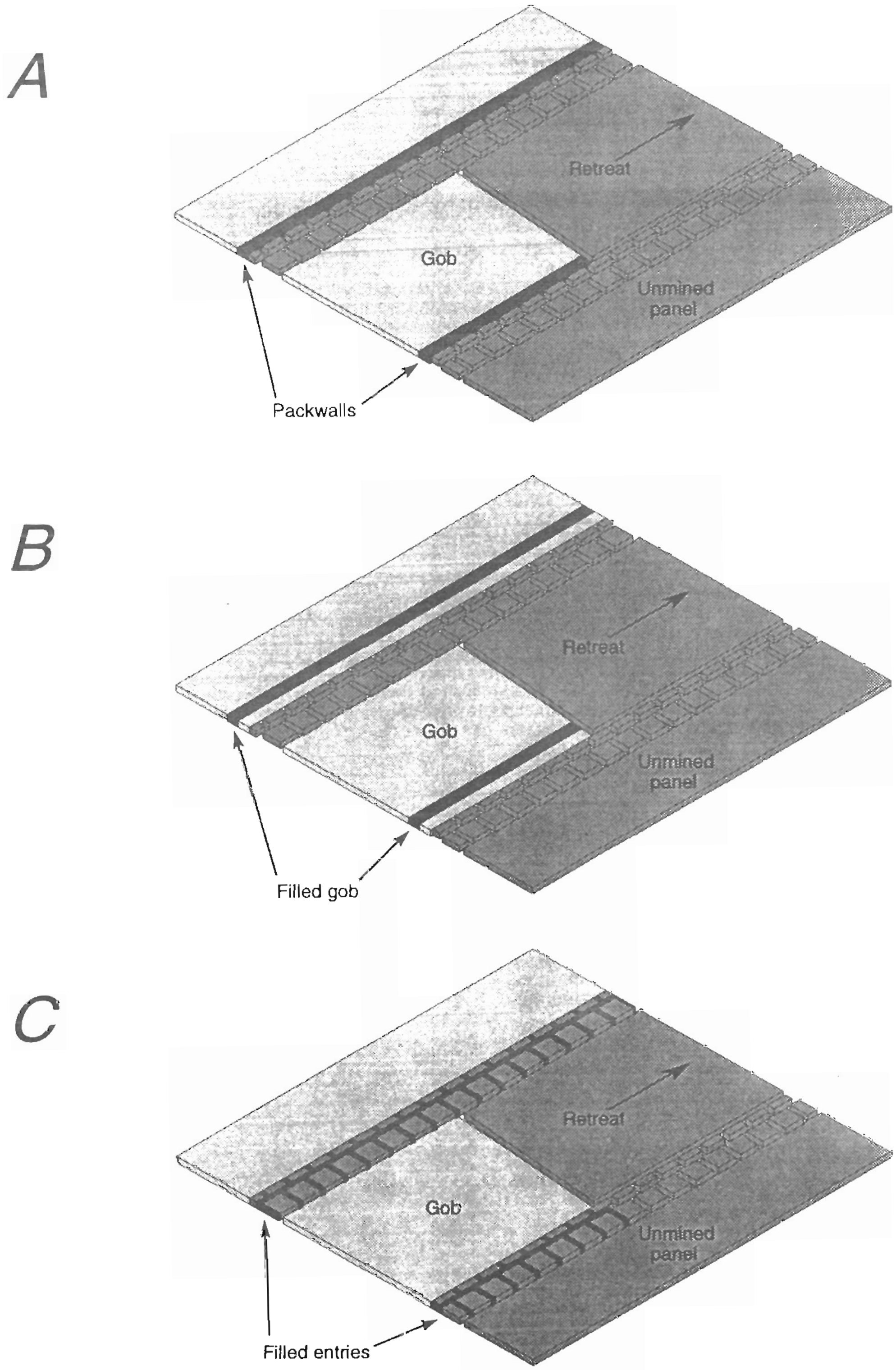

Figure 1.- Stress transfer modification concepts. A, Packwalling; B, gob infilling; C, entry filling.

Control section

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        3
    2.00.525E+04.150E-01.226E+04.235E-01.250E+00
    2.00.105E+05.300E-01.300E+04.514E-01.250E+00
   11.00.500E+04.500E+05.226E+04.300E+01.250E+00
    0.00
    0.0.0696     0.0.0184     0.0.0000     0.0.1333     0.0.0000     0.0.0917
  600.00       21       15                        6        16        6       10
     0.0      0.0-24600.0     66.0
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    1.35  100.00      500                                   1        1
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Fine mesh

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Coarse mesh

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Figure 2.- Typical MULSIM/NL input file.

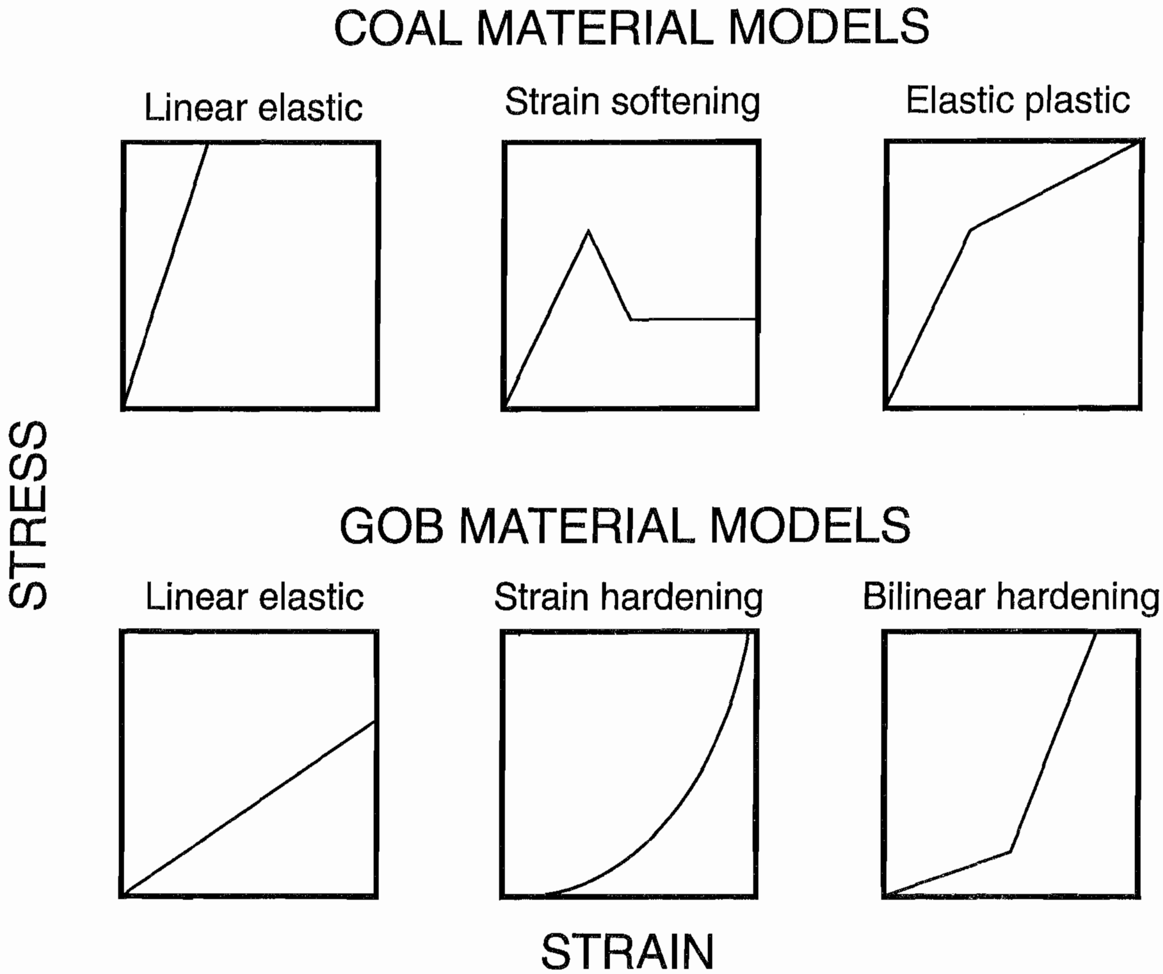


Figure 3.- Material property types available in MULSIM/NL.

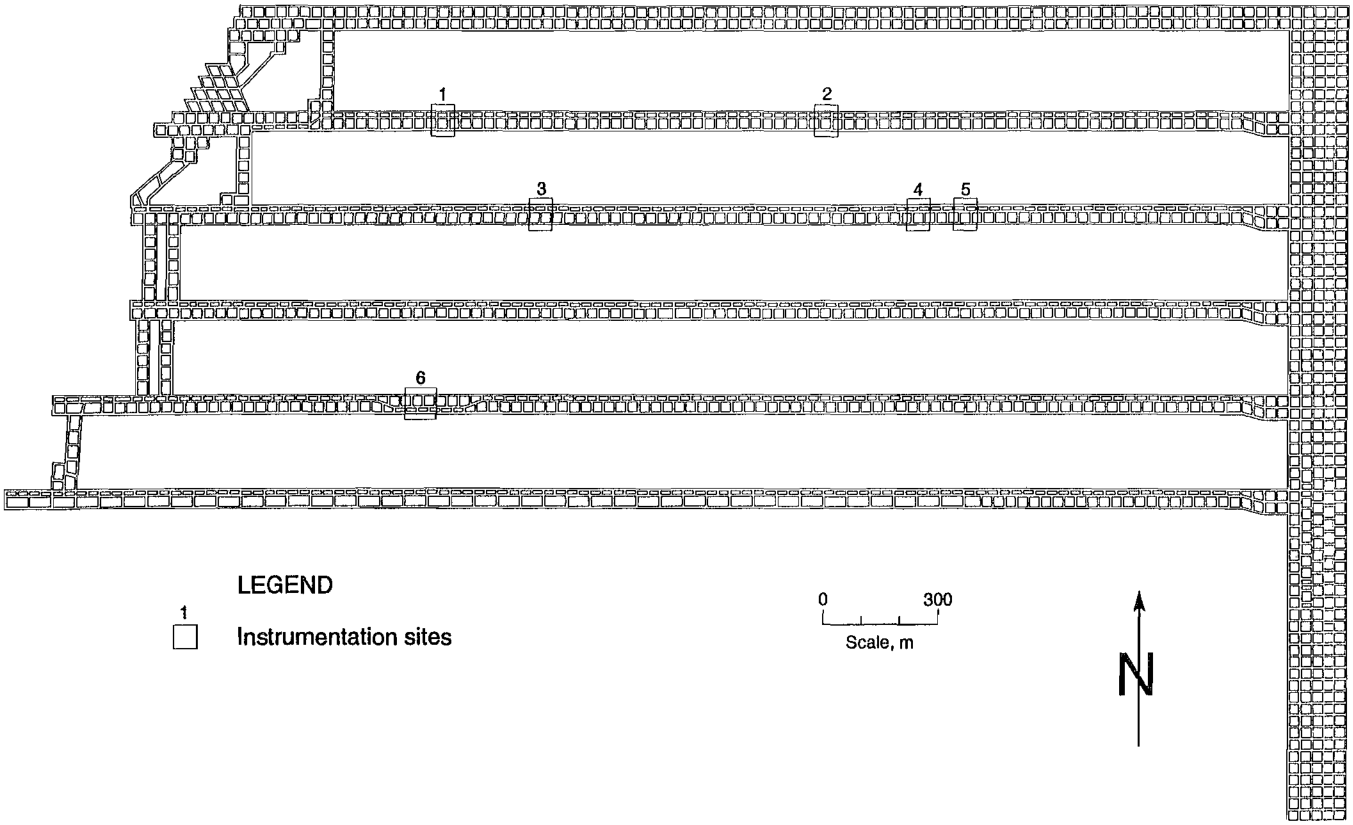


Figure 4.- General layout of the western longwall coal mine used to develop and test the intermediate depth baseline model.

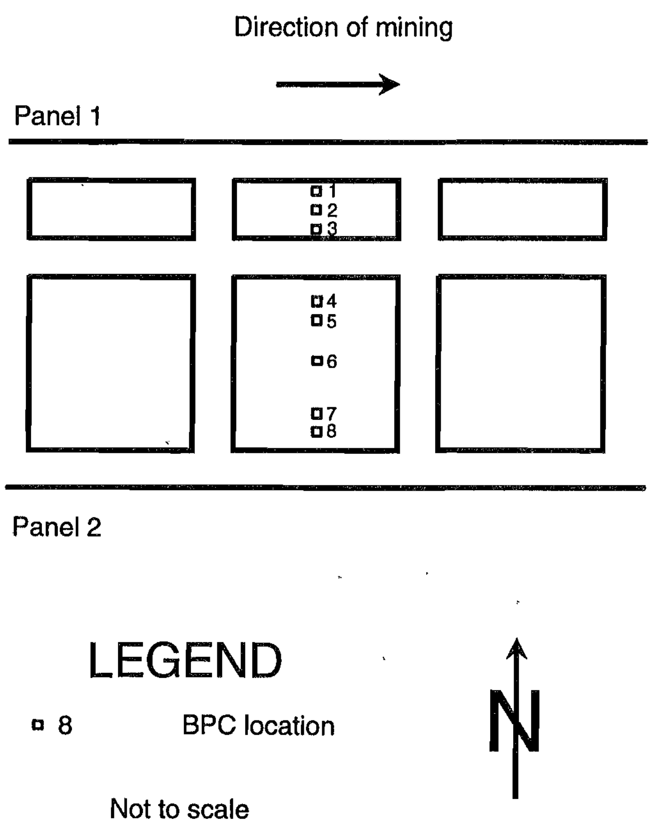


Figure 5.- Pressure cell locations at instrument site 2, intermediate depth mine.

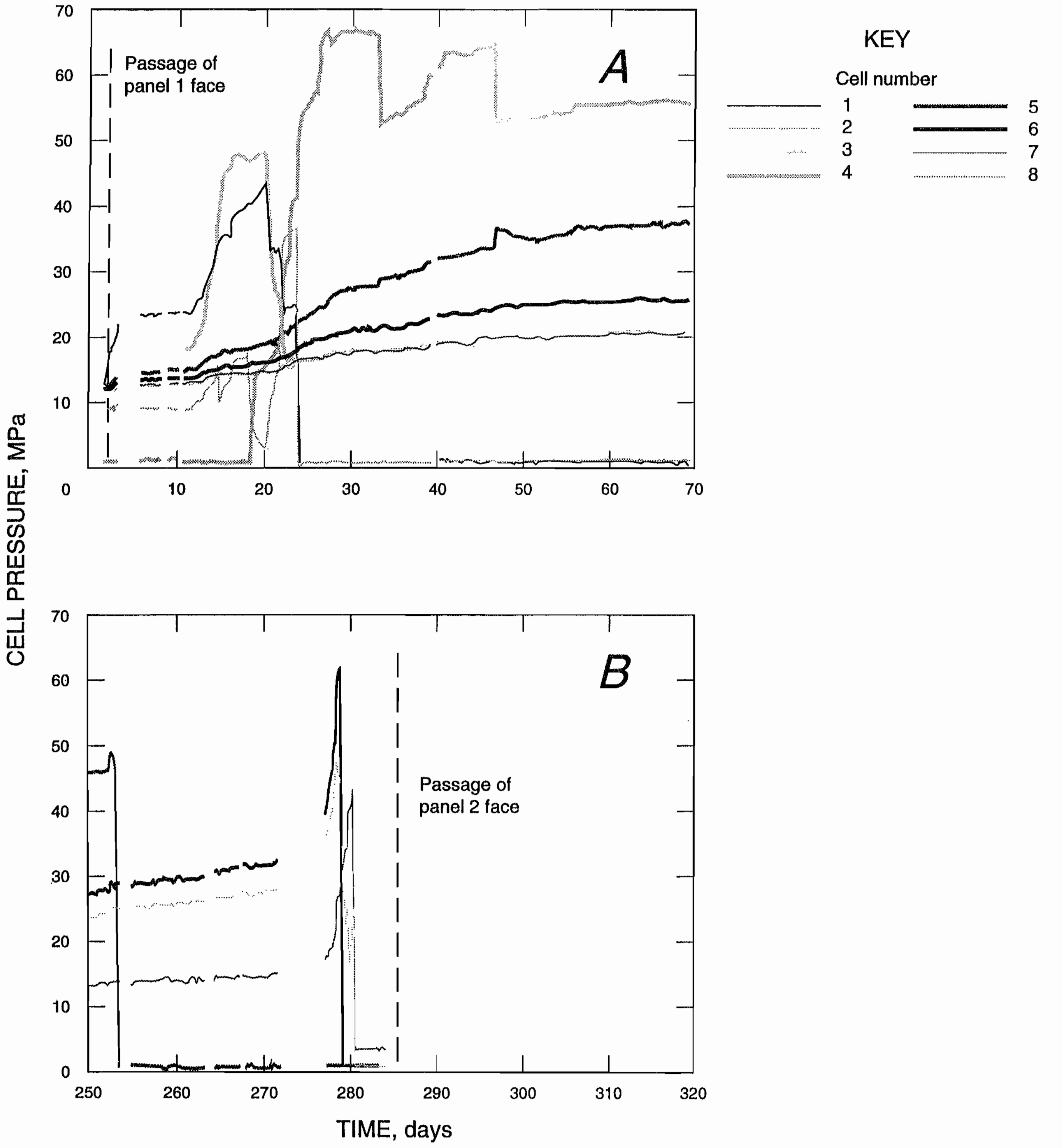


Figure 6.- Typical BPC readings, instrumentation site 2. A, During panel 1 mining; B, during panel 2 mining.

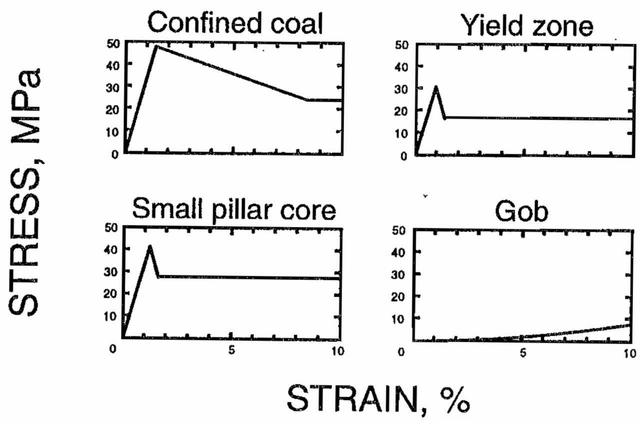


Figure 7.- Seam element stress-strain curves, intermediate depth baseline model.

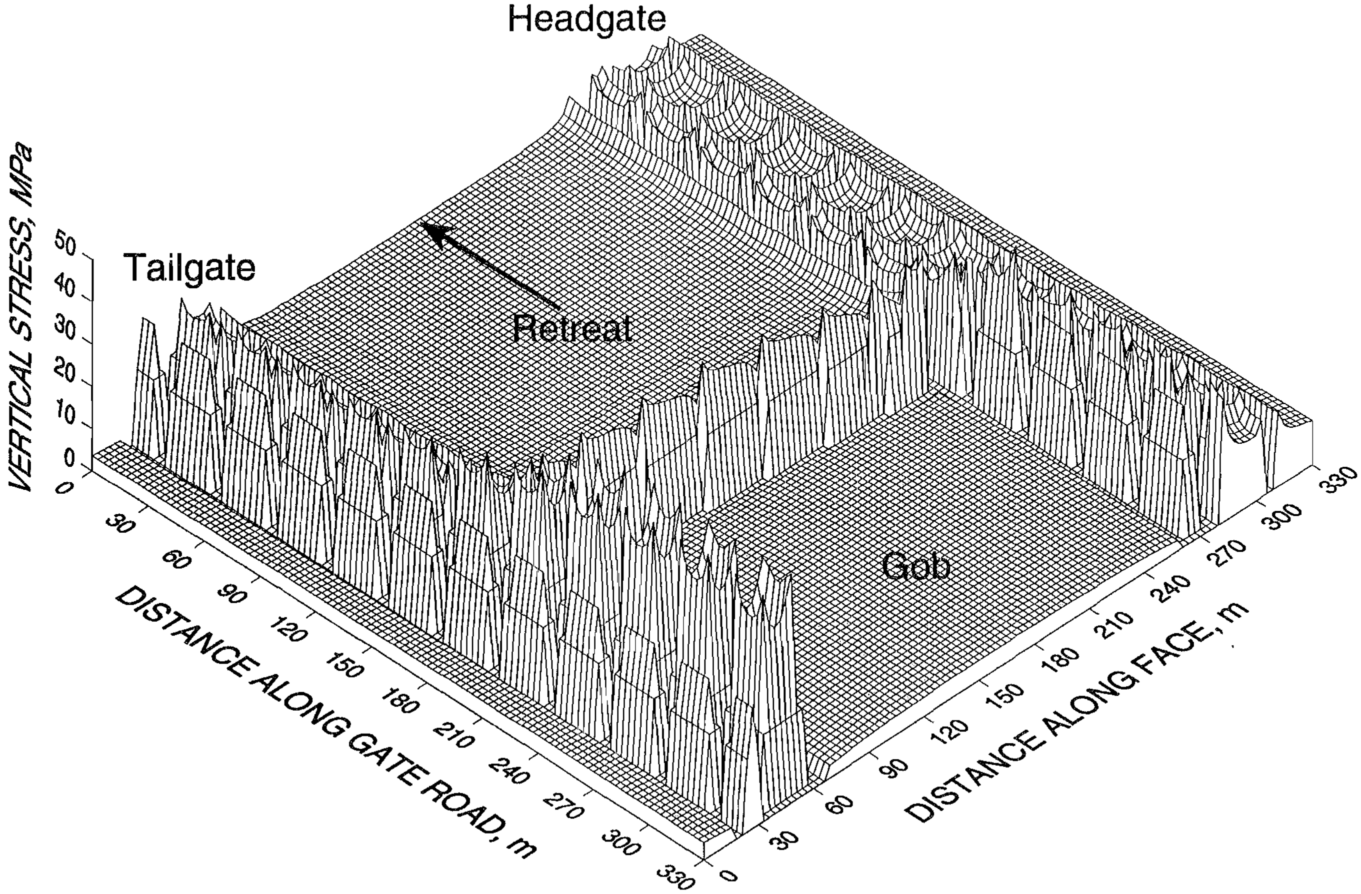


Figure 8.- Vertical stress distribution, intermediate depth baseline model.

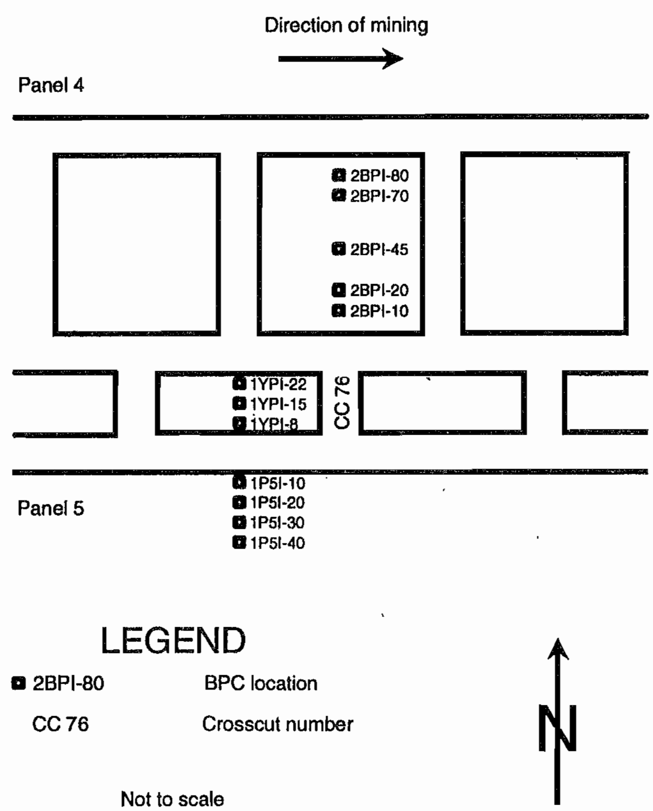


Figure 9.- Experimental gate road layout and location of instrumentation.

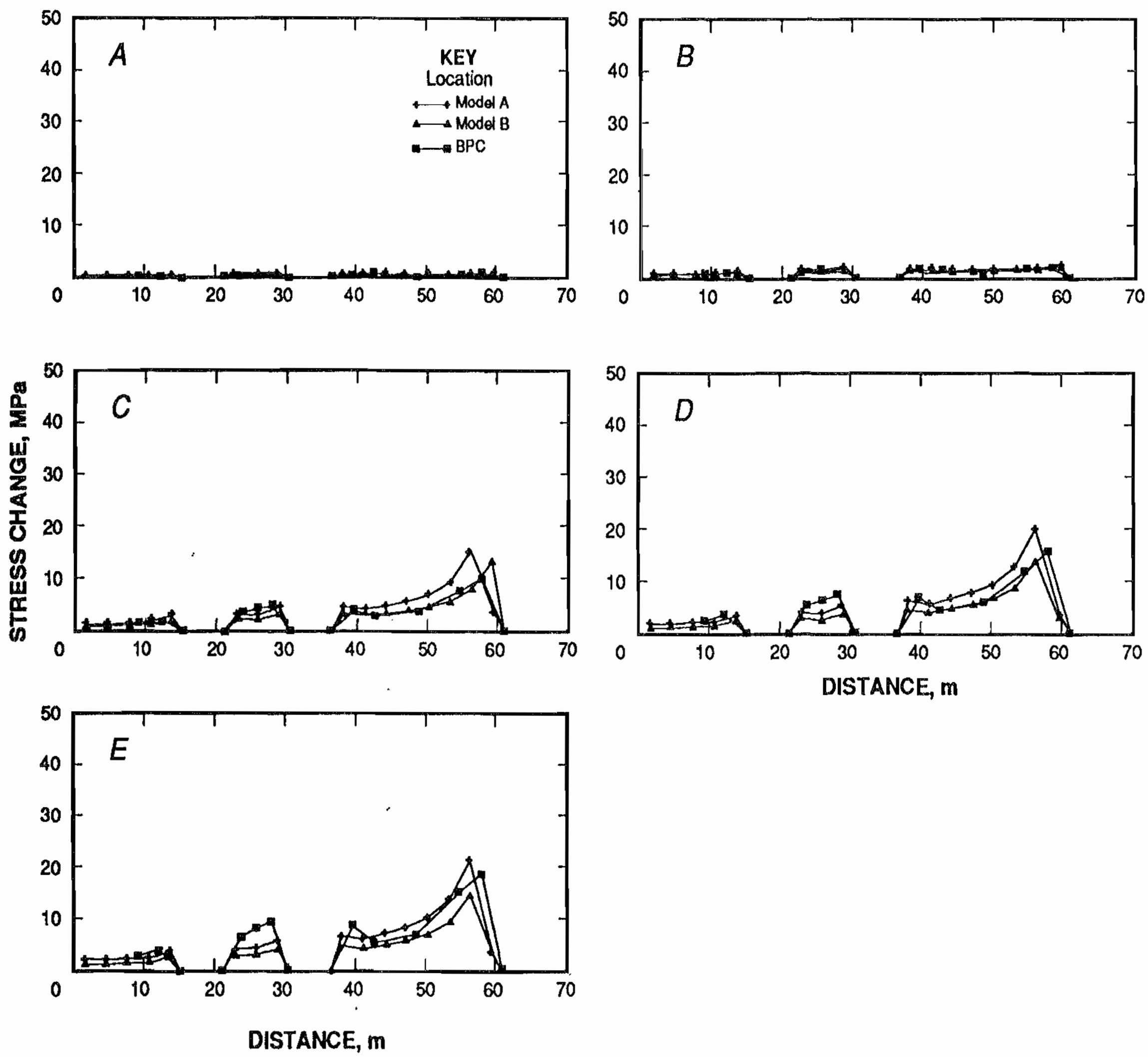


Figure 10.- Comparison of modeling and pressure cell data for the experimental gate road test site during panel 4 mining. A, Face 76 m (250 ft) inby measurement line; B, 15 m (50 ft) inby; C, 46 m (150 ft) outby; D, 107 m (350 ft) outby; E, 168 m (550 ft) outby.

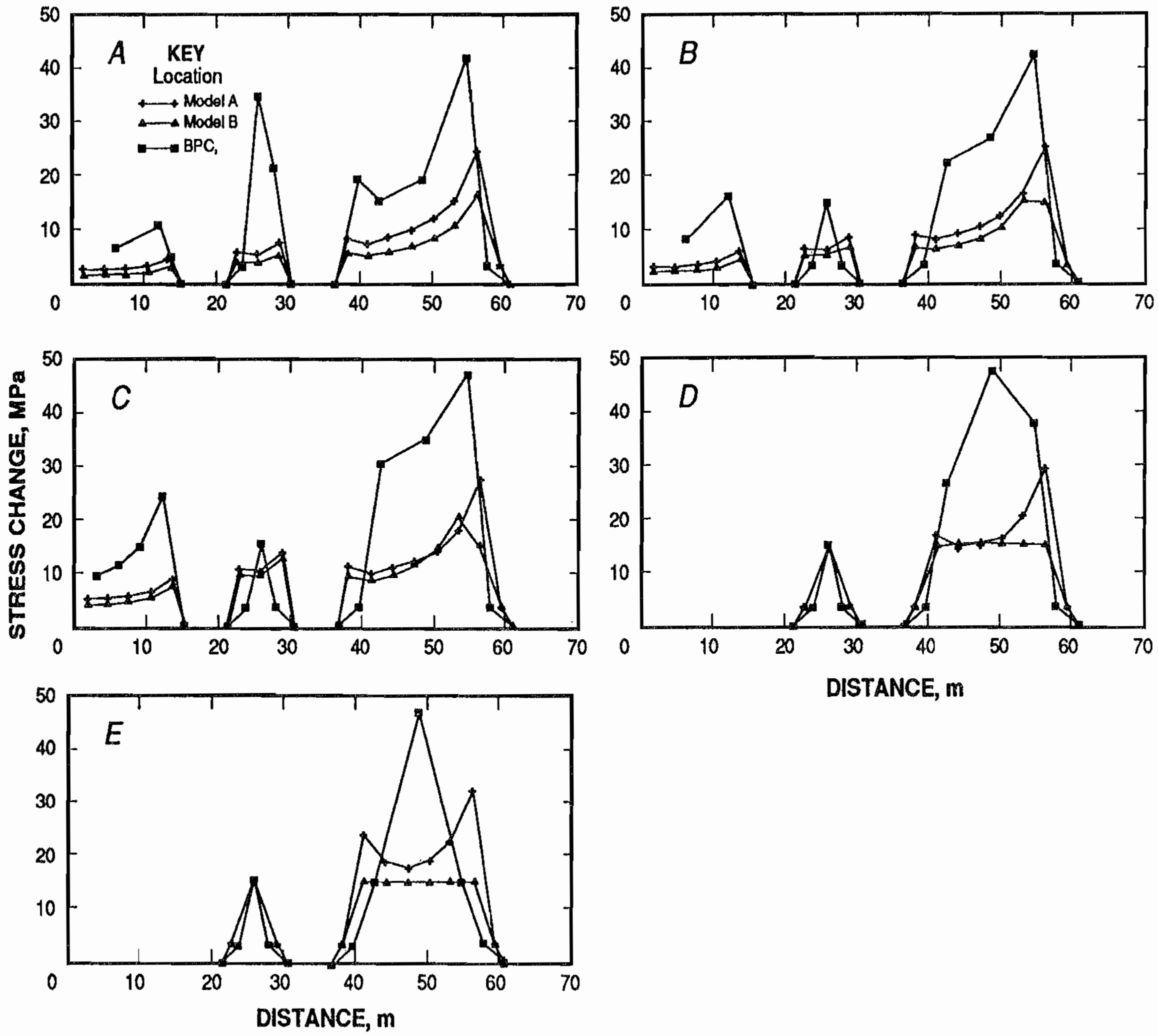


Figure 11.- Comparison of modeling and pressure cell data for the experimental gate road test site during panel 5 mining. A, Face 91 m (300 ft) inby measurement line; B, 61 m (200 ft) inby; C, 30 m (100 ft) inby; D, face even with measurement line; E, face 30 m (100 ft) outby.

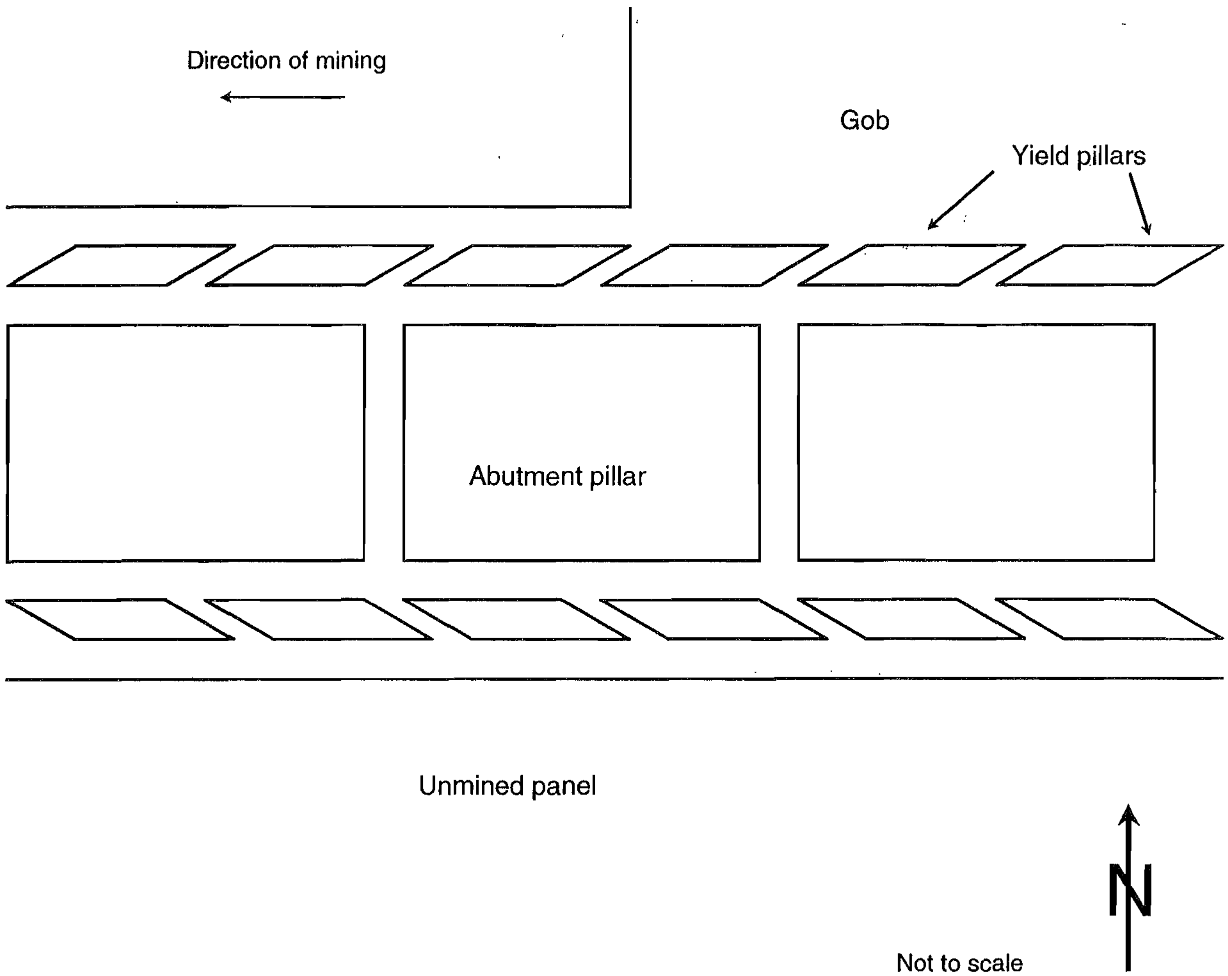


Figure 12.- General layout of the eastern longwall coal mine used to develop the deep baseline model.

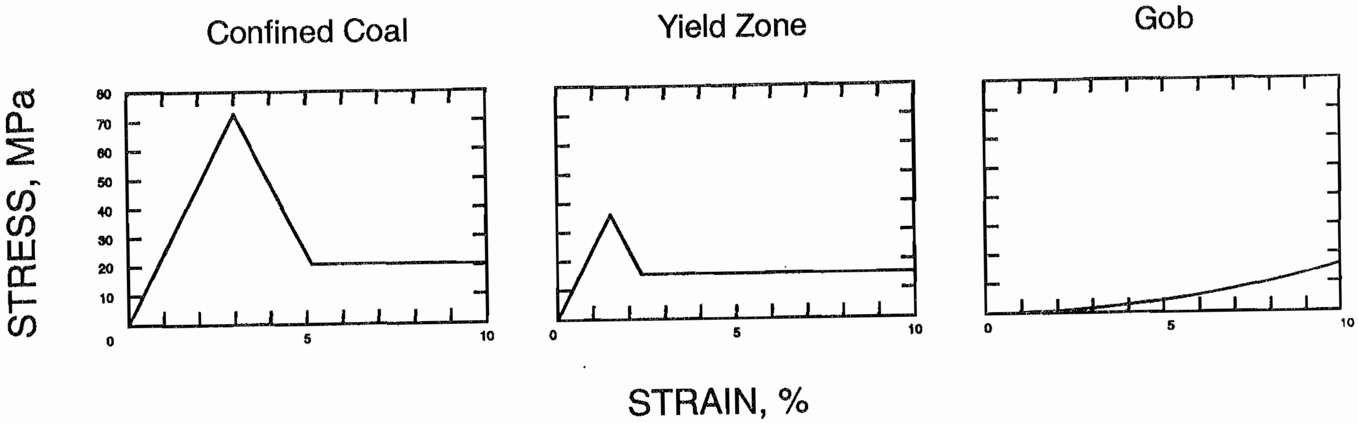
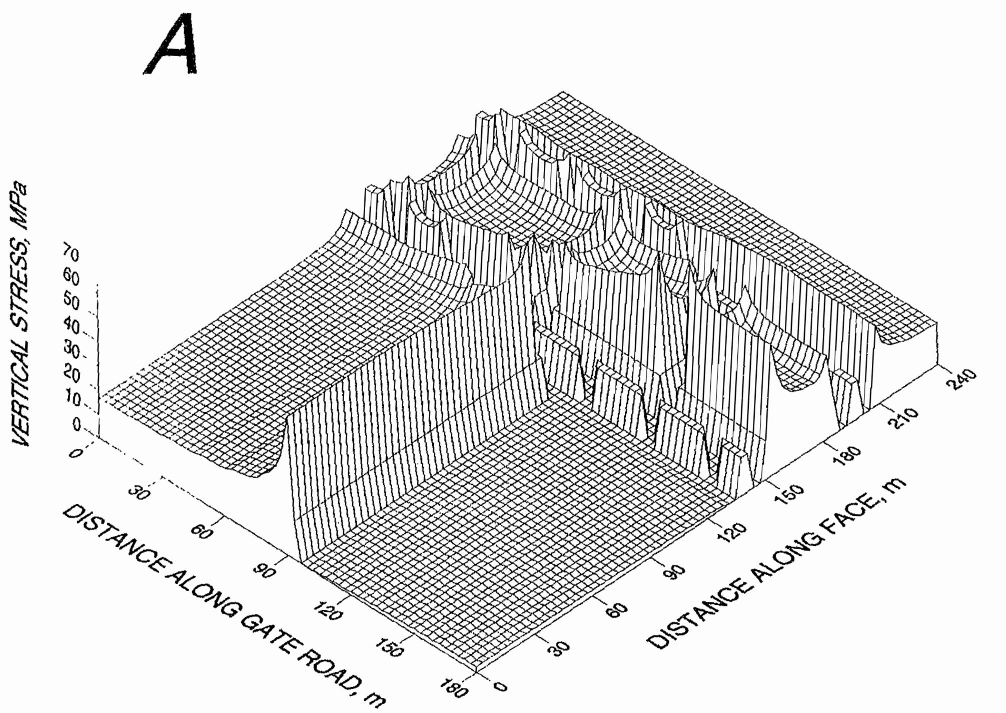


Figure 13.- Seam element stress-strain curves, deep baseline model.



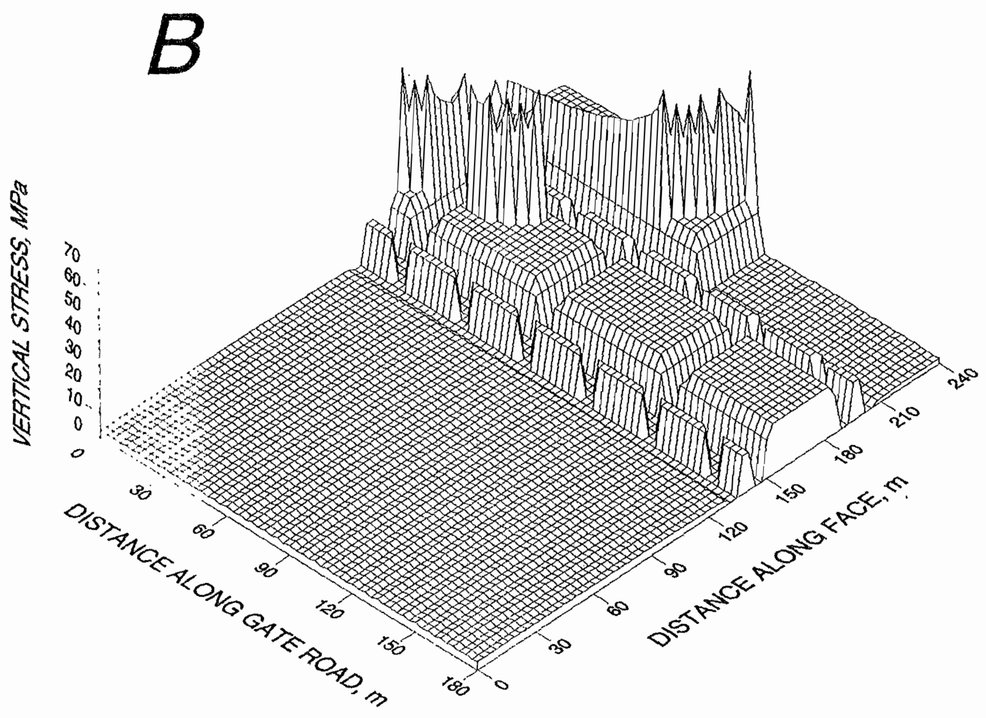


Figure 14.- Vertical stress distribution, deep baseline model. A, Headgate; B, tailgate.

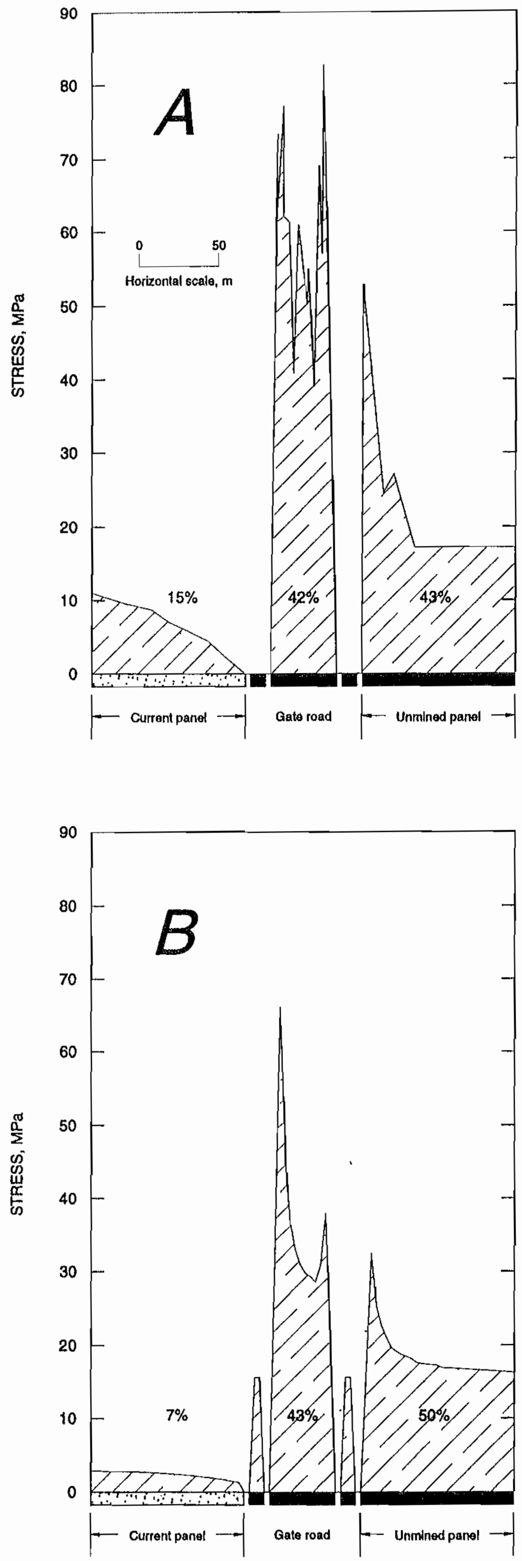


Figure 15.- Vertical stress distribution with the face 152 m (500 ft) outby the measurement line, fir. panel mining. A, Field measurements reported by Campoli (17); B, results from the deep baseline model.

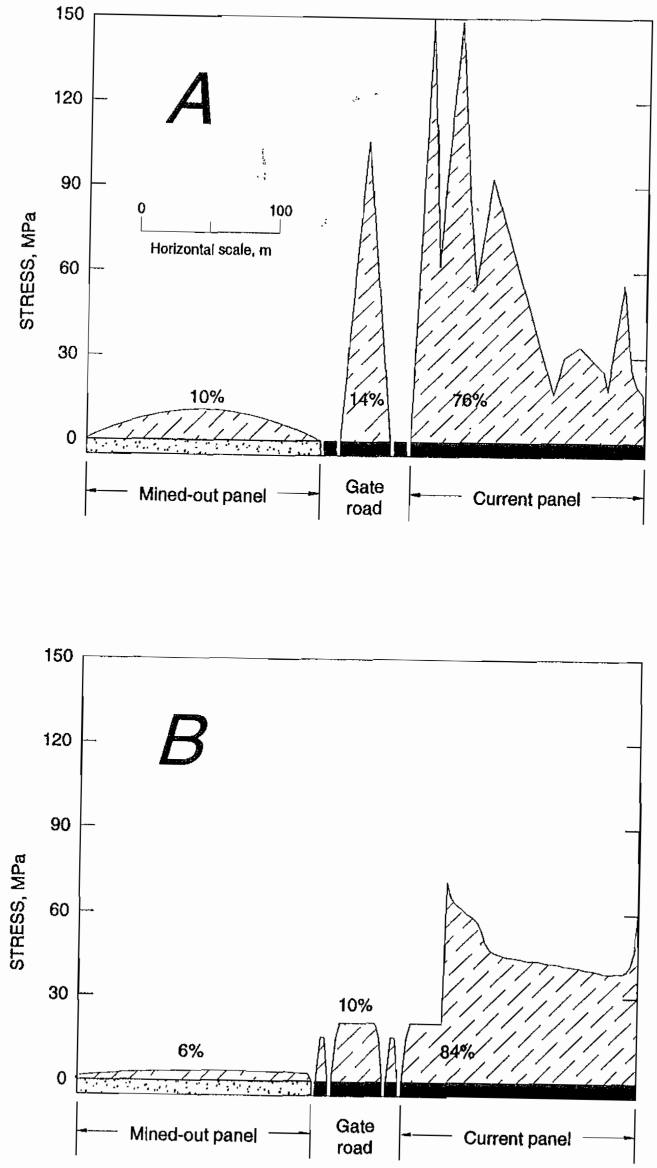


Figure 16.- Vertical stress distribution with the face 6 m (20 ft) inby the measurement line, second panel mining. A, Field measurements reported by Campoli (17); B, results from the deep baseline model.

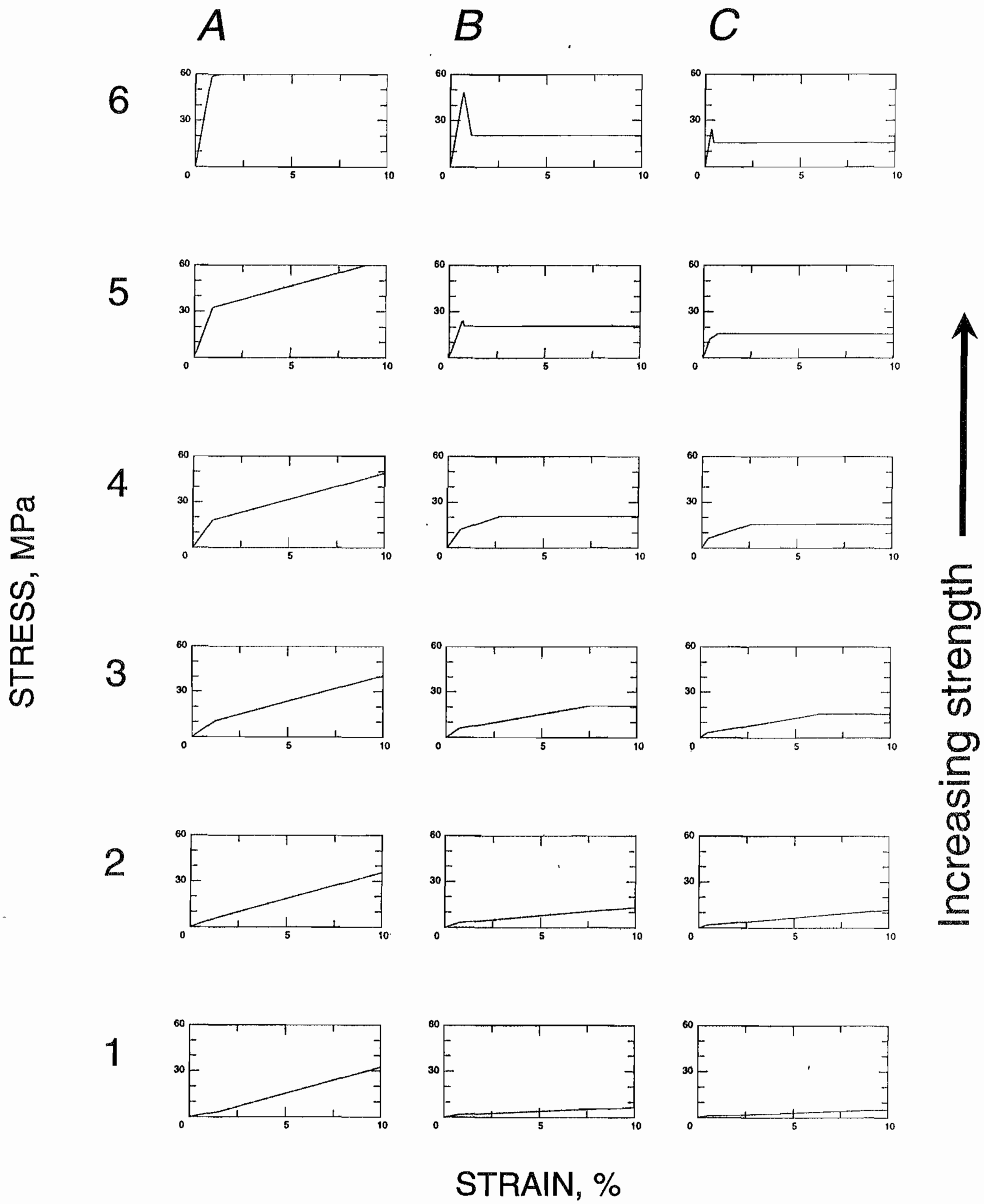


Figure 17.- Stress-strain relationships for modeled fill materials. A, Gob fill; B, confined monolith. fill; C, unconfined monolithic fill.

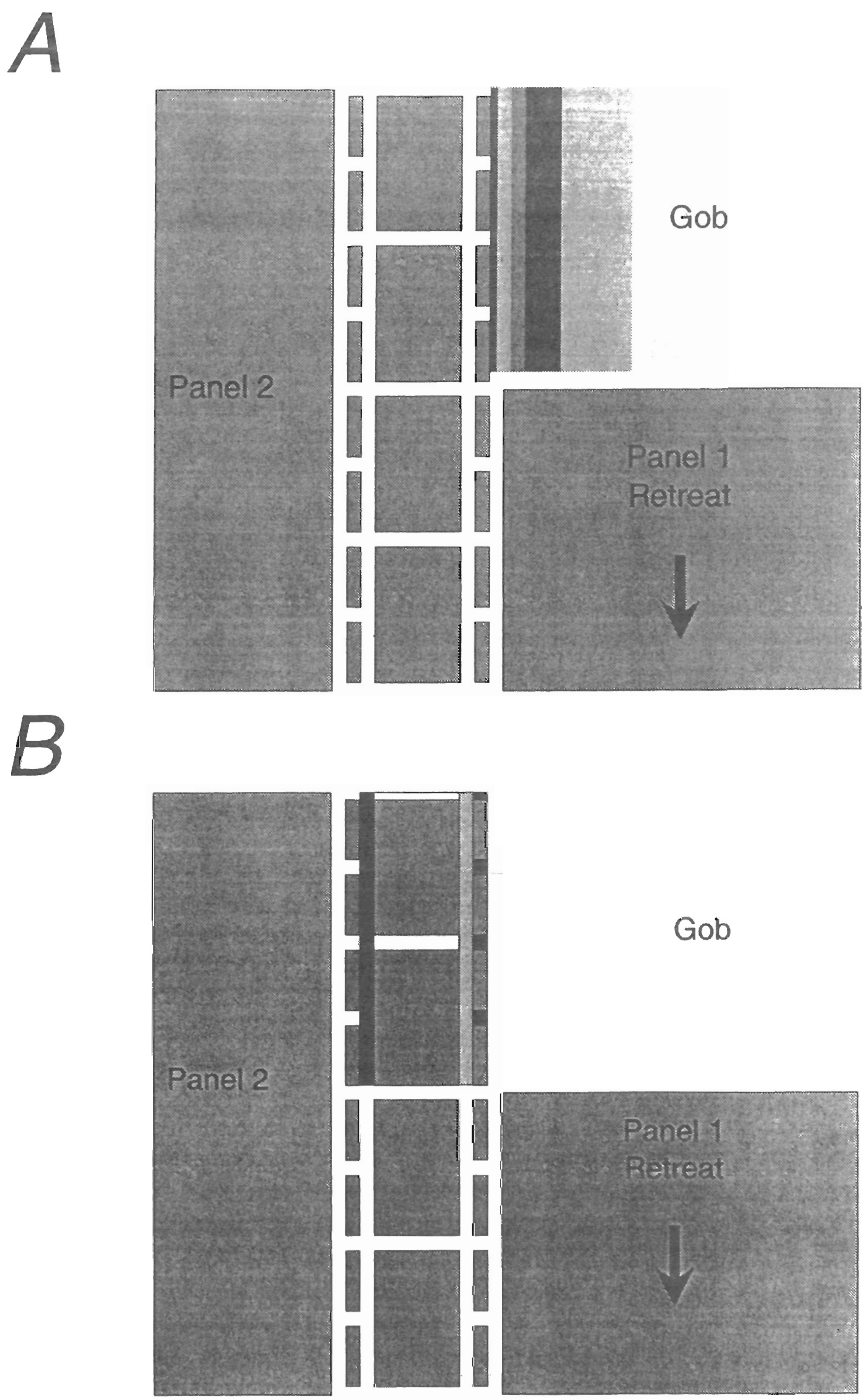


Figure 18.- Fill geometries for A, the packwalling and gob infilling concepts, and B, for the entry filling concept.

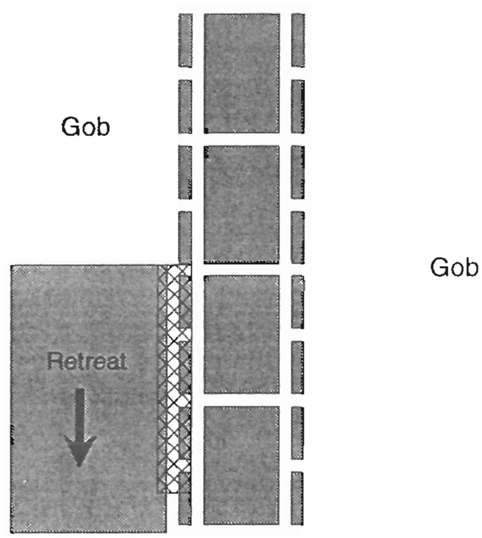


Figure 19.- Area of tailgate closure calculation.

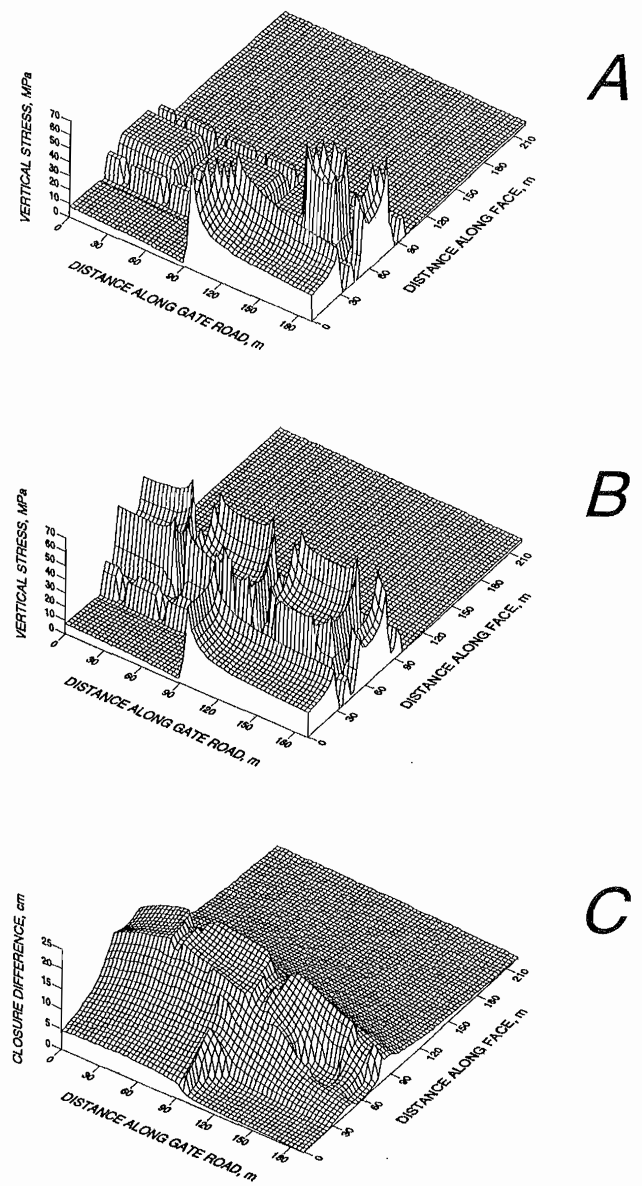


Figure 20.- Example of modeling analysis results. A, Vertical stress distribution, deep baseline model; B, vertical stress distribution, deep baseline model with entry filling; C, reduction in closure between the two models.

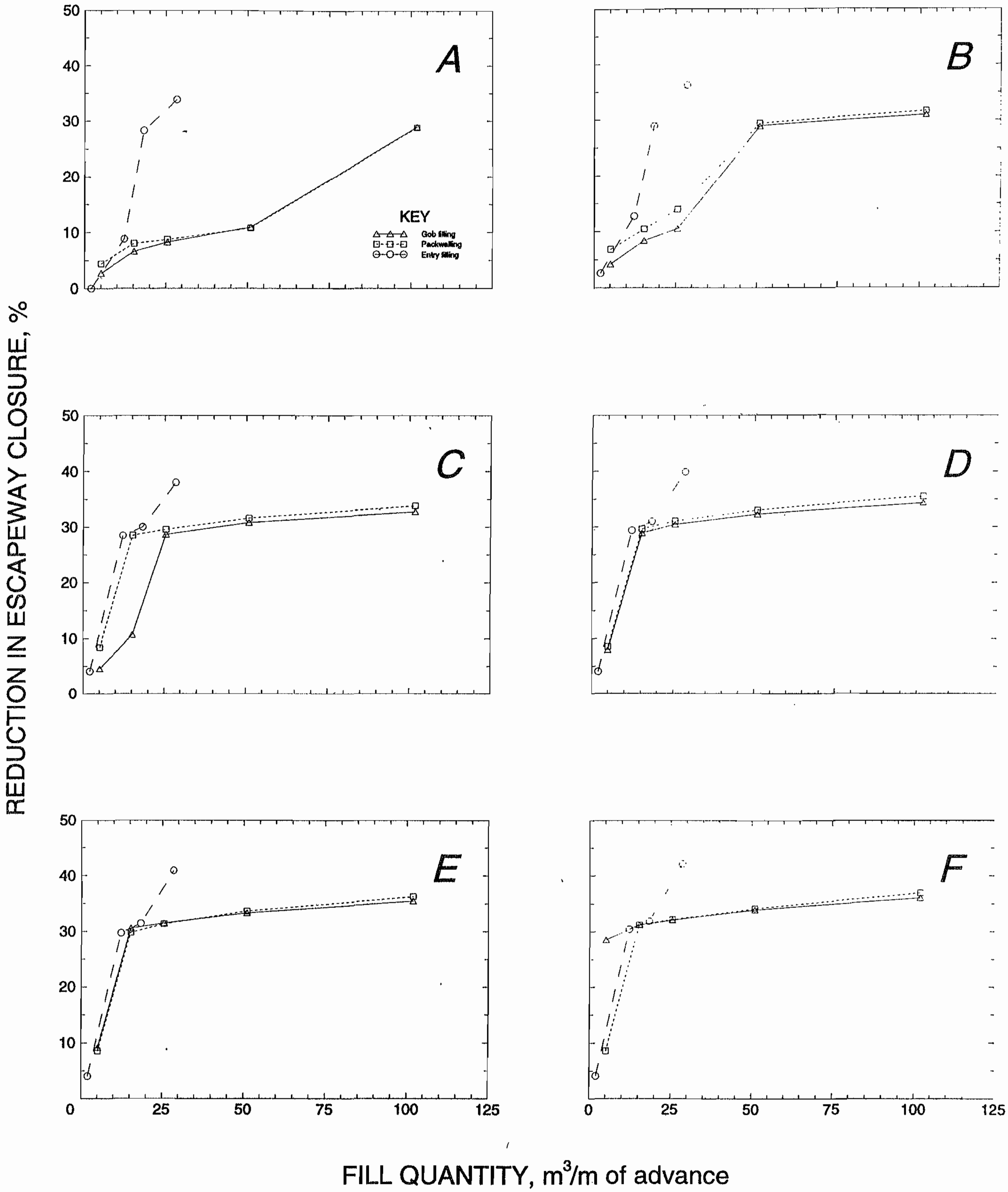


Figure 21.- Reduction in escapeway closure as a function of fill volume for the three stress transfer modification concepts, from the weakest fill modeled (A) to the strongest (F).

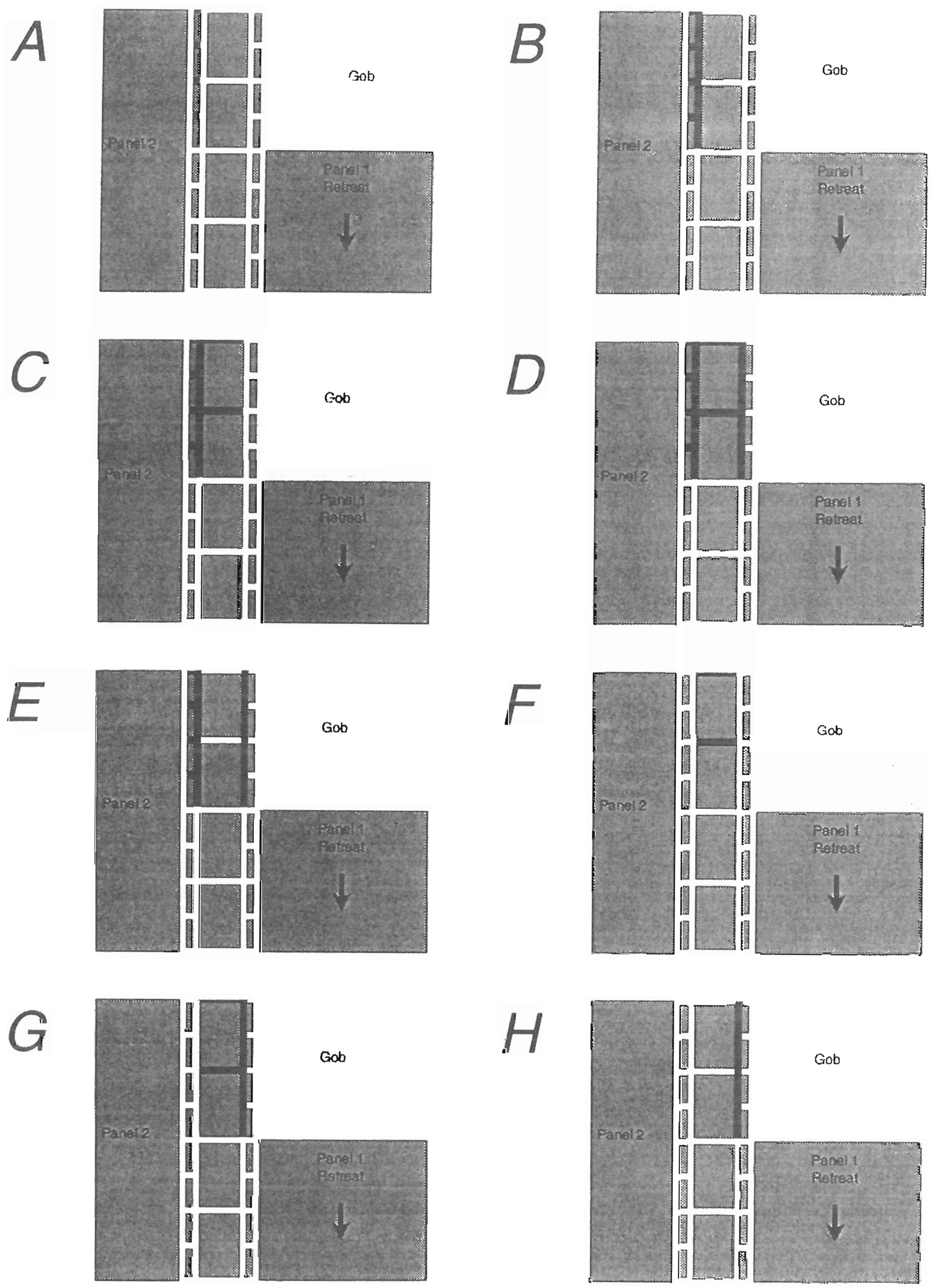


Figure 22.- Fill geometries for the detailed analysis of the entry filling concept. Geometries A through E allow for one open entry in the tailgate; geometries F through H allow for two open entries.

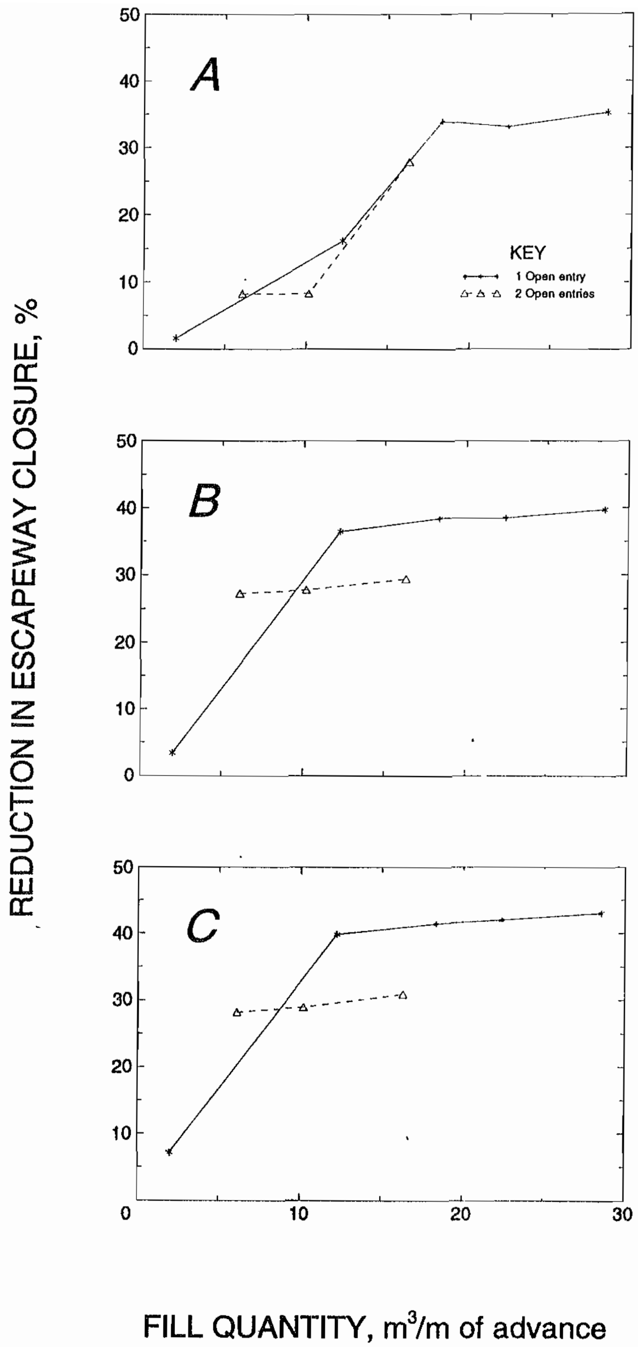


Figure 23.- Reduction in escapeway closure as a function of fill volume for the entry filling concep analysis, from the weakest fill modeled (A) to the strongest (C).